TITAN ORBITER WITH AEROROVER MISSION (TOAM)

E. C. Sittler Jr.(1), J. F. Cooper(1), P. Mahaffy(1), J. Esper(1), D. Fairbrother(2), R. Farley(1), J. Pitman(3), D. R. Kojiro(4), M. Acuna(1), M. Allen(5), G. Bjoraker(1), J. Brasunas(1), M. J. Burchell(6), M. Burger(1), G. Chin(1), A. J. Coates(7), W. Farrell(1), M. Flasar(1), B. Gerlach(8), S. Gorevan(9), R. E. Hartle(1), Eastwood Im(5), D. Jennings(1), R. E. Johnson(10), W. T. Kasprzak(1), H. W. Kunow(11), S. Livi(12), H. Niemann(1), J. Nuth(1), D. J. McComas(13), R. MacDowall(1), B. McKibben(14), R. Pfaff(1), F. Raulin(15), D. Reuter(1), F. Robb(16), D. Schulze-Makuch(17), R. Wimmer-Schweingruber(18), P. Siegel(5), D. E. Smith(1), A. Steele(18), J. Trombka(1), Y. Yung(19), and J. C. Zarnecki(20)

(1)NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA, Email: Edward.c.sittler@nasa.gov
(2)NASA-GSFC Wallops Flight Facility, Wallops, VA, USA, Email: Debora.A.Fairbrother@nasa.gov
(3)Lockheed Martin-ATC, Palo Alto, CA, USA, Email: joe.pitman@lmco.com
(4)NASA Ames Research Center, Moffett Field, CA, USA, Email: dkojiro@mail.arc.nasa.gov
(5)Jet Propulsion Laboratory, Pasadena, CA, USA, Email: mark.allen@jpl.nasa.gov
(6) University of Kent, Canterbury, Kent CT2 7NH, UK, Email: m.j.burchell@ukc.ac.uk
(7) Mullard Space Science Laboratory, University College London, Dorking, UK, Email: ajc@mssl.ucl.ac.uk
(8) Rockwell Collins Deutschland GmbH, Grenzhöfer Weg 36, Heidelberg, Germany, Email: bernd_bs@gmx.de
(9) Honeybee Robotics, Ltd., New York, NY, USA , Email: gorevan@honeybeerobotics.com
(10) University of Virginia, Charlottesville, VA, USA, Email: rej@virginia.edu
(11) University of Kiel, Keil, Germany, Email: kunow@physik.uni-kiel.de
(12) Applied Physics Laboratory, Laurel, MD, USA, Email: stefano.livi@jhuapl.edu
(13) Southwest Research Institute, San Antonio, TX, USA, Email: dmccomas@swri.edu
(14) University of New Hampshire, NH, USA , Email: Bruce.McKibben@unh.edu
(15) LISA- University of Paris, France, Email: raulin@lisa.univ-paris12.fr
(16) University of Maryland Biotechnology Institute, Baltimore, MD, USA, Email: robb@umbi.umd.edu
(17) Washington State University, Pullman, WA, USA, Email: dirksm@mail.wsu.edu
(18) Carnegie Institution of Washington, D. C., USA, Email: a.steele@gl.ciw.edu
(19) California Institute of Technology, Pasadena, CA, USA, Email: yly@mercu1.gps.caltech.edu
(20) Open University, Milton Keynes, UK. Email: j.c.zarnecki@open.ac.uk

ABSTRACT

We propose to develop a new mission to Titan called Titan Orbiter with Aerorover Mission (TOAM). This mission is motivated by the recent discoveries of Titan, its atmosphere and its surface by the Huygens Probe, and a combination of in situ, remote sensing and radar mapping measurements of Titan by the Cassini orbiter. Titan is a body for which Astrobiology (i.e., prebiotic chemistry) will be the primary science goal of any future missions to it. TOAM is planned to use an orbiter and balloon technology (i.e., aerorover). Aerobraking will be used to put payload into orbit around Titan. The Aerorover will probably use a hot air balloon concept using the waste heat from the MMRTG ~ 500 watts. Orbiter support for the Aerorover is unique to our approach for Titan. Our strategy to use an orbiter is contrary to some studies using just a single probe with balloon. Autonomous operation and navigation of the Aerorover around Titan will be required, which will include descent near to the surface to collect surface samples for analysis (i.e., touch and go technique). The orbiter can provide both relay station and GPS roles for the Aerorover. The Aerorover will have all the instruments needed to sample Titan's atmosphere, surface, possible methane lakes-rivers, use multi-spectral imagers for surface reconnaissance; to take close up surface images; take core samples and deploy seismometers during landing phase. Both active and passive broadband remote sensing techniques will be used for surface topography, winds and composition measurements.

1. INTRODUCTION

Titan is presently listed as a high-priority future mission in the 2003 *Solar System Decadal Survey*, as well as in the June 2006 draft of the emerging *NASA Science Plan*. The Cassini/Huygens results have further elevated scientific priority for a mission to Titan. In this mission an orbital spacecraft 1200 km above Titan's extended atmosphere, works in concert with a hot air balloon, the Aerorover, globally traversing Titan at about 10km/hr. The mission will feature global radar sounding, both passive and active laser remote sensing from the orbiter, global sampling of Titan's surface and atmosphere, along with close-range reconnaissance from the Aerorover.

In the case of Titan, there is now evidence of methane river beds, lakes and surfaces possibly saturated with methane and other hydrocarbons [1]. Titan's upper atmosphere and ionosphere is now known to be dominated by a very rich hydrocarbon chemistry [2, 3] producing precipitates raining down to Titan's surface where further complex chemistry can take place. The presence of methane in the atmosphere (detected *in situ* by the Huygens probe [4]), ~ 2% in upper atmosphere and ~ 6% at surface, means it must be continuously replenished (lifetime ~ 10 Myrs; [5]) from Titan's interior and thus Titan must be geologically active. There is indirect evidence from observation of horizontal clouds [6] that cryo-volcanism may be an ongoing process at Titan. Evidence for fluvial processes has been detected by Cassini cameras and radar [7,8], while Huygens cameras show evidence of methane rain [1] and constant methane drizzle [9]. Recently, Cassini radar has discovered methane or ethane lakes at Titan's North Polar Cap [*Cassini-Huygens News Release 2006-097*].

Originally, a Titan only mission called "Titan Orbiter Aerorover Mission" (TOAM) was put forth in a Goddard-led proposed 2003 *Vision Missions* Study by *Sittler et al.*, [2003] [10]. In that study, reviewed in our Figures 1, 2 and 3, they proposed a hot air balloon concept. The advantage of the hot air balloon is that the mass of the inflatable gas is not brought from Earth. Furthermore, over time the gas will eventually diffuse across the walls of the balloon and escape, thus limiting the balloon lifetime. A hot air balloon has an infinite reservoir of gas, so long as the energy source duration is unlimited, essentially true for an RTG power source. An orbiter is needed to avoid long blackout periods when the balloon is not facing Earth and the orbiter can provide global positioning information for the balloon's navigation system.

As presently conceived, TOAM is a multi-faceted mission with launch using a Delta IV Heavy for high C3 interplanetary orbit injection, possible Jupiter flyby, Solar Electric Propulsion (SEP), orbit injection around Titan via aerobraking at Titan, probe entry with balloon technology (i.e., aerorover phase) and finally a landing phase. Mission phase durations include 5-9 years for cruise to Saturn, and six months each for orbiter reconnaissance, aerorover global reconnaissance, aerorover global surface science and aerorover landing. There could be an extended phase for orbiter-lander science operations.The orbiter is planned to be powered by 3 MMRTGs and Aerorover by a single MMRTG. The Aerorover will probably use a hot air balloon concept using the waste heat from the MMRTG ~ 500 watts.

Our orbiter-Aerorover approach is unique and provides assurance for a successful long-term mission. Autonomous operation and navigation of the Aerorover around Titan, which will include descent near to the surface to collect surface samples for analysis, is in itself a very complex process and will require nearly continuous tracking and navigation updates. Only an orbiter can provide this capability as a relay station and GPS role so that the Aerorover will be able to navigate safely within Titan's environment, while maintaining nearly continuous communication with ground stations. Although very complex, our goal is to keep the Aerorover as simple as possible in order to enhance the likelihood of success. Experience has shown that such complex missions will develop unexpected problems, for which a balloon concept allows for it to safe itself by going to high altitudes. This allows teams on the ground the necessary time needed to work around such problems. New technologies will need to be

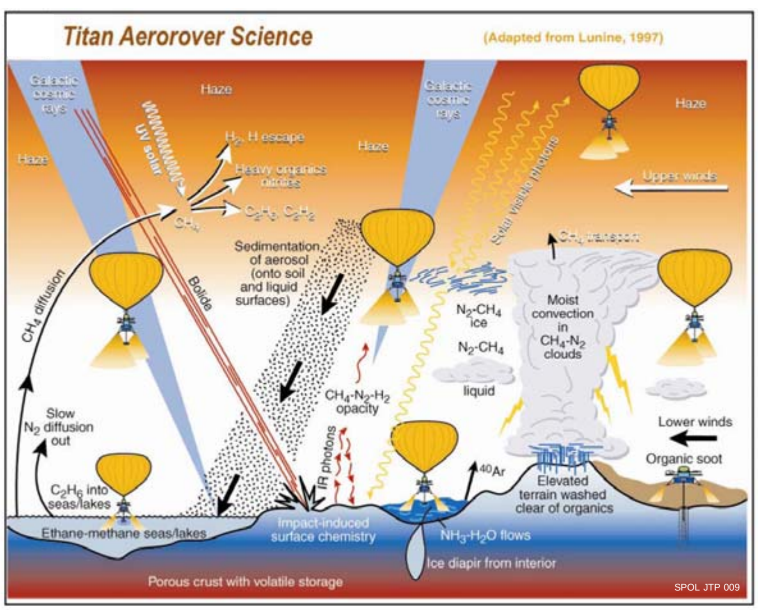

Figure 1 TOAM Aerorover Science Concept

developed and miniaturization will be required to maintain functionality while controlling mass, power and cost. Duty cycling will be used. The orbiter will combine altimetry, radio science and remote sensing instruments to measure the global topography, sub-surface structure and atmospheric winds during its recon phase. The Aerorover can then use this information to navigate safely around Titan and identify prime sites for surface sampling and analysis. In situ instruments will sample the upper atmosphere which may provide the seed population for the complex organic chemistry on the surface. The Aerorover will have all the instruments needed to sample Titan's atmosphere, surface, and possible methane lakes-rivers. In flight it will also use multi-spectral images for surface reconnaissance and take close up surface images. Surface core sampling and seismic measurements can be carried out during the final landed phase.

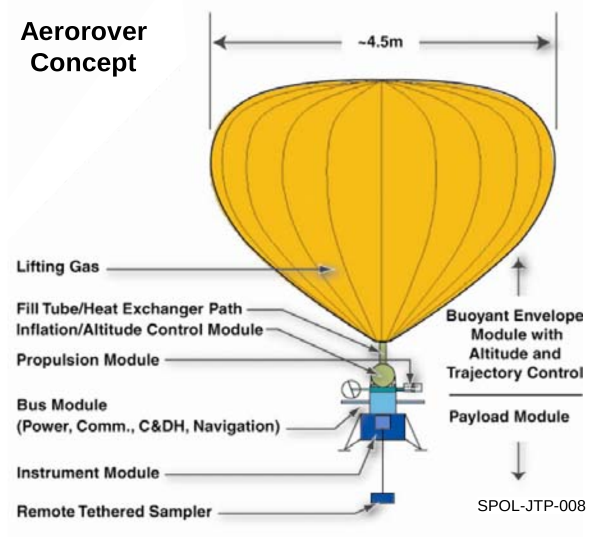

Figure 2 TOAM Aerorover Concept Design

3. IMPLEMENTATION APPROACH

3.1 Mission Design

TOAM leverages the planned maturation of a number of advanced technologies. They range from advanced chemical propulsion systems to power generation and aerocapture, advanced imaging systems, miniaturized instruments and aerorover technologies. This section summarizes major elements.

Mission operational phases will be:

- Launch and orbit injection; (after 2013)
- Cruise and midcourse corrections, which may include gravity assist maneuvers; (5 to 9 years)
- Saturn/Titan orbit insertion with possible tour with Enceladus as primary target and then obit insertion at Titan
- Orbiter science/reconnaissance; (6 months)
- Aerorover science; (12 months)
- Surface science; (6 months).

Total science mission operations is 2 years, from Titan orbit insertion to end of surface operations. Extended science operation capabilities from the orbiter would be included.

Transfer orbit from Earth to Titan can be achieved using either chemical propulsion alone or a combination of solar electric (SEP) and chemical propulsion. Preliminary studies indicate the SEP option will deliver a higher payload mass for a given launch vehicle and hence is the baseline. In this case, the low-thrust trajectory assumes the SEP

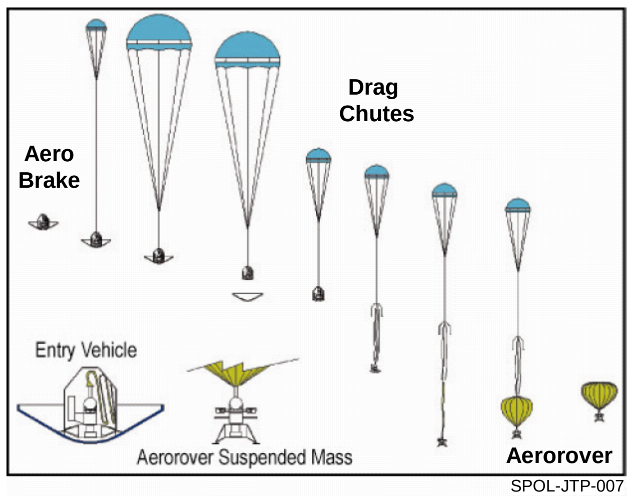

Figure 3 TOAM Aerorover Insertion

system will only be operated within 2 to 3 AU from the Sun, and ejected beyond. The spacecraft then continues operating with its chemical propulsion system. The Titan orbit will be achieved using a combination of chemical propulsion and aerodynamic forces. Aerocapture into the Saturnian system is the baseline scenario. Titan will be used to provide the initial aerocapture ΔV for injection into either a Saturn or a direct Titan orbit. The former requires a lower expenditure of fuel initially but necessitates a second pass near Titan for orbit insertion. The latter implies a larger initial ΔV and aerothermodynamic heat loads but may provide for a quicker start to science operations. Delayed Titan orbit entry allows opportunities for flybys of other high-interest Saturn moons including Enceladus.

For one study we had the Earth-Saturn trajectory for a SEP case with no gravity assist. The initial 14-hour elliptical polar science orbit (also shown) affords a close approach to Titan for radar and radio science measurements, and provides for an extended picture of its particles and fields environment. The orbit would then be circularized for surface mapping and aerorover release and tracking. Orbit radius may be raised to minimize blackout periods for aerorover.

Aerorover entry into Titan's atmosphere occurs after a 6-month period of orbital surface mapping and science reconnaissance. The entry sequence is shown in Figure 3, and includes aerodynamic braking with the aeroshell, parachute deployment, buoyant envelope deployment, and parachute release. This marks the onset of one year of science operations, leading to the 6-month surface landing phase. Landing may be achieved by slowly deflating the buoyant envelope until touchdown, and immediately detaching the envelope module to prevent the material from covering the payload module. The Aerorover phase then ends and transitions to the final fixed lander phase with continuing support from the orbiter.

3.2 Titan Orbiter

The orbiter houses the remote-sensing instruments, provides health and safety services to the aerorover during the cruise and orbit phases, transmits data to and from the aerorover, and communicates with the Deep Space Network (DSN). It also executes concurrent science operations during the aerorover and surface phases.

The baseline communications approach is to use Ka-band to downlink science data and X-band for uplink of commands and downlink of engineering telemetry. This approach also provides the required dual-band coverage for radio science observations. Assuming a 2-m high gain antenna (HGA), Reed-Solomon encoding, a maximum compressed data volume of 1.5 Gbits, a DSN 70-m equivalent antenna, and 86 kbps downlink rate, downlink time is about 5 hours. Data acquisition management and advanced encoding techniques are also assumed. Alternatively, use of optical communications will be explored during the study.

Three Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) yield ~ 300W of power. Details of a power management scheme using these and alternative radioisotope power systems need to be developed. A single Stirling Radioisotope Generater (SRG) probably would be used for the aerorover with ~ 100 W of electricity and ~ 500 W of waste heat..

The combined spacecraft-Aerorover payload is housed within a protective aeroshell, which provides thermal protection during aerocapture. The aerorover will have its own heat shield for entry into Titan's atmosphere. Modular and reconfigurable spacecraft architecture design principles are an important technology identified for future development.

3.2.1 Candidate Orbiter Science Instruments

Advanced remote sensing with high spatial and spectral resolution is essential to achievement of orbiter science goals. A facility class telescopic system, such as Lockheed Martin's Multiple Instrument Distributed Aperture Sensor (MIDAS) payload (see Figure 5), will be required for active and passive imaging. Lidar technologies will be used to produce surface topology maps needed for Aerorover navigation near the surface.

Titan Radio Science (TRS) will use both X- and Ka-band systems with ultra-stable oscillators for atmosphere-ionosphere radio occultation measurement, and use a "two-way" coherent tracking mode for gravity measurements. The combination of MIDAS-Lidar and TRS will provide the topographic and gravity measurements to allow detection of a subsurface ocean and determine crustal thickness [11, 12, 13]. The combination of the Titan Submillimeter Limb Sounder (TSLS), and Titan Infrared Spectrometer (TIRS), both integrated with MIDAS, and use of the wind equation will allow measurement of the global zonal wind pattern down to the surface. TSLS will use a two-channel submillimeter wave heterodyne radiometer system, while TIRS is an improvement to the Cassini Composite Infrared Spectrometer.

The fields and particles instrument package deals with the complex interaction of Saturn's magnetosphere (or solar wind/magnetosheath) with Titan's upper atmosphere and the corresponding upper atmospheric organic and elemental composition. This instrumentation also addresses induced complex current systems that can affect Aerorover measurement of electric and magnetic fields near the surface. Furthermore, the package quantifies the role of cosmic rays in Titan's middle atmosphere in providing ionization energy to the organic chemistry.

3.3 Aerorover

The Aerorover provides the platform to conduct *in-situ* sampling of Titan's atmosphere and surface at multiple locations. Aerorovers are ideally suited for this type of mission because these airborne platforms can travel above the surface at controlled altitudes and can cover greater areas than traditional surface vehicles. Close-up surface imaging of Titan; chemical, atmospheric and magnetometer measurements; and periodic surface sampling are all possible with the Aerorover regardless of surface composition.

The Balloon Program Office (BPO) at GSFC's Wallops Flight Facility (WFF) is NASA's center for ballooning technology development, design, and operations management. With its long and successful history of scientific ballooning, from conventional zero-pressure balloons to current superpressure ultra long duration balloon (ULDB) development, BPO is developing advanced balloon technologies for both terrestrial and Mars applications. Our partnership with Lockheed Martin will provide extensive knowledge in the balloon technology area from their High Altitude Balloon Program.

3.3.1 Aerorover Requirements

Science mission goals drive the following preliminary Aerorover requirements:

- Altitude control at 0-10 km;
- Highest priority scientific instruments;
- Ground track trajectory control;
- Survival of 5 to 9 year cruise, orbit insertion, and atmospheric deployment;
- Acquisition and analysis capability for surface and subsurface samples.

3.3.2 Candidate Aerorover Science Instruments

We now list possible candidate aerorover instruments, for which some were derived from the Huygens instrument package [14]. Resources will be a limiting factor for instrument selection. To begin, Gas Chromatigraph Mass Spectrometer (GCMS) measurements are key to achieving the TOAM requirements relating to the nature and complexity of prebiotic chemistry at Titan. The Aerosol Collector Pyrolyzer (ACP) uses a stainless steel filter to collect aerosols and retract into a chamber for later analysis by the GCMS. Microarray Assay for Titan Exploration (MATE) can detect large complex organic molecules such as peptides, proteins, and DNA fragments. The Titan Ice and Dust Experiment (TIDE) instrument will be used to collect both liquid and surface samples, store these in appropriate canisters, and then use, for example, pyrolosis to deliver the effluent gases to the GCMS. The Titan Neutron/Gamma-Ray Instrument (TNGRI), lowered near the surface by tether, will measure elemental and mineralogical chemistry to ~10 cm depth. The Atmosphere Properties Unit (APU) is composed of accelerometers, electric and magnetic field probes, a temperature sensor, pressure gauge, and acoustic and conductivity sensors. The Liquid Properties

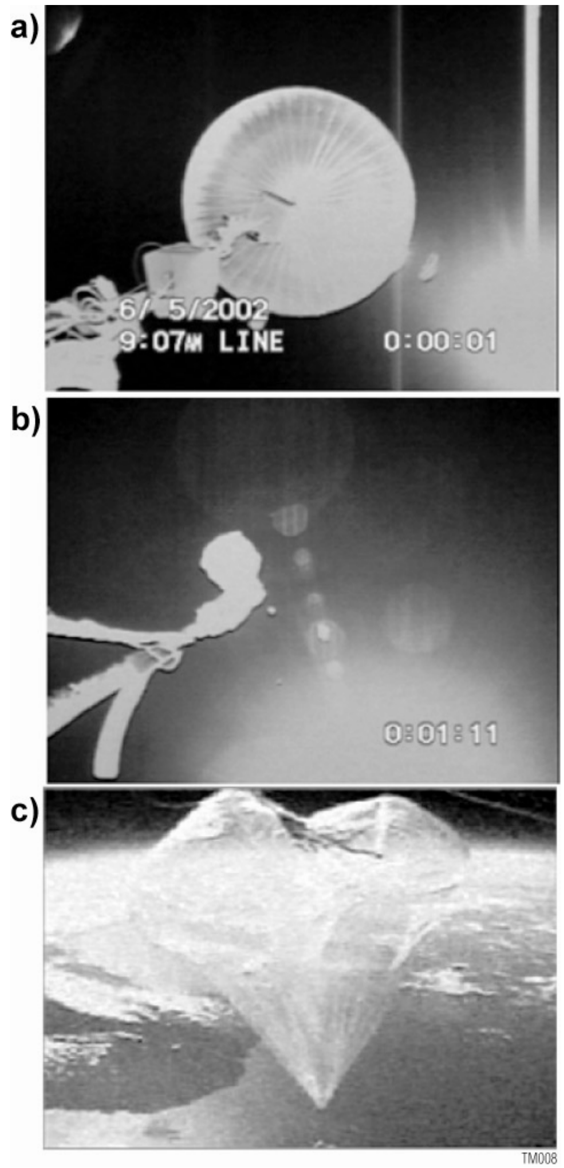

Figure 4 Successful aerial deployment and inflation of Goddard/Wallops prototype Mars pumpkin balloon. (a) upward view of carrier balloon just prior to deployment; (b) upward view of prototype balloon just after deployment; (c) side view of Mars prototype during descent (island of Hawaii in background).

Unit (LPU) uses sonar for lake depth and speed of sound measurements, temperature and density sensors for fluids, and a tiltmeter for measurement of surface waves and tides [15]. The Surface Properties Unit (SPU) will measure surface stiffness, uniformity and granular structure (sands, grit, gravel) [15] and have a magnetometer to measure crustal magnetism [16] and conduct induced magnetic field surveys in conjunction with external field measurements by the orbiter. A miniature version of LM's MIDAS would be used for Lidar altimetery and wind measurements (i.e., Doppler off of aerosols) and multi-spectral measurements for surface composition to name a few.

3.3.3 Aerorover Development Approach

The Aerorover must be stowed for several years, receive power and data from the orbiter, and deploy and inflate while descending through the Titan atmosphere. After deployment, the Aerorover must travel about Titan, obtain detailed imaging of Titan's surface, collect and analyze surface samples at numerous locations, and transmit the information to the orbiter. At the end of the aerial portion of the mission, the instrument package must safely land to collect and conduct detailed analyses of surface and subsurface samples. The data are then transmitted to the orbiter for relay to Earth.

The proposed concept poses several key Aerorover design and operational questions:

- What buoyant envelope design will permit the required altitude control?
- What trajectory control system will provide the greatest mission flexibility?
- What materials will survive transit, atmo-spheric entry and, deployment and perform in the Titan environment?
- What level of autonomy is required for Aerorover operations?
- How and when will information be exchanged between the orbiter and the Aerorover?
- How will the Aerorover safely land the instrumentation package on the surface?
- How will the Aerorover be constructed and handled to ensure that its surfaces are free of bioburden?

Mission requirements and extreme environmental conditions present unique vehicle design challenges and opportunities. The extreme temperatures of Titan require buoyant envelope materials to perform at temperatures that are much lower than any previously studied. If hot air balloon concept is not used, then lifting gas must be transported from Earth or generated *in-situ.* The vehicle must be capable of autonomous or semi-autonomous trajectory control for latitude, longitude and altitude control. The aerorover must be capable of interacting with Titan's surface to collect and analyze surface samples.

With regard to deployment, Titan's dense atmo-sphere enables sufficient time for the entry, deployment, and inflation sequence, as shown in Figure 3. BPO's ability to aerially deploy and inflate a planetary balloon for Mars was suc-cessfully demonstrated in June 2002 as shown in Figure 4. This experience, combined with research in packaging technologies will aid in providing a sound basis for continuing development.

Finally, any future mission to Titan with entry vehicle will require consideration of planetary protection.

4. TECHNOLOGY DEVELOPMENT

Our goal is to fit within the cost cap of New Frontiers for our TOAM concept. Our approach to achieving this goal is to establish partnerships with industry such as Lockheed Martin's MIDAS concept, High Altitude Balloon technology, missile defence technologies for atmospheric entry probes and RTG technologies. We will also take advantage of the capabilities offered by Ames Research Center (ARC) when it comes to astrobiology, aerocapture technologies, and planetary protection. Finally, we will look to develop new technologies in the area of miniaturization such as microelectronics, MEMS technology, sensor miniaturization and nanotechnology. We want to reduce mass, power

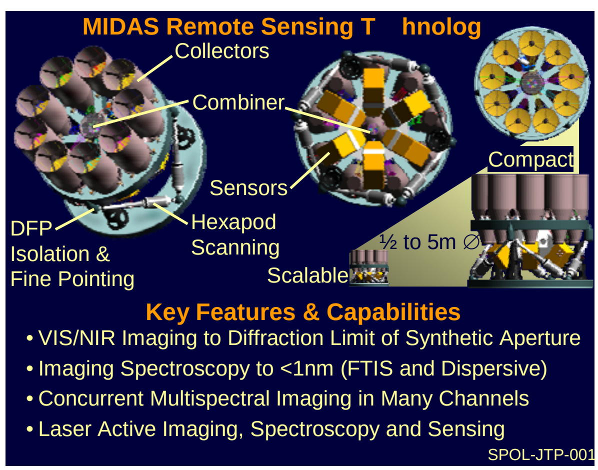

Figure 5 LM MIDAS Payload Technology

and volume while maintaining functionality. Work is already in progress when it comes to spacecraft miniaturization [17] and we plan to take advantage of these new technologies. Such technologies would be used for both the orbiter & Aerorover. We will briefly describe three key technologies actively being considered.

4.1 MIDAS Concept

Reconnaissance is a major element of the TOAM concept with active and passive imaging playing a major role in this process. LM's MIDAS testbed system [18, 19] can be considered a facility of telescopes which can be used individually and together as a phased array to provide affective aperture sizes ~ 1 meter. This technology has been developed by LM for a number of applications. This will greatly reduce the risk and cost of our TOAM mission. We plan to develop the interfaces between passive (spectroscopic measurements) and active (Lidar) imaging concepts. For the orbiter we would use a version of MIDAS having an effective aperture ~ 1 meter and for the balloon a lightweighted version with an effective aperture ~ 30-50 cm. The MIDAS telescope system has the capability to isolate itself from the spacecraft with 60bD of broadband attenuation, featuring precise pointing needed for its very high resolution active and passive imaging of Titan, Enceladus and the Saturnian system, before and during the Titan orbiter phase. This vibration isolation is very important as the Aerorover moves through atmospheric turbulence. On the balloon, a mini-version of MIDAS can provide altimetry data so that balloon can provide direct altimetry data, also supplemented by radar and sonar techniques, to assure safe navigation near the surface and avoidance of potentially hazardous surface topography, such as hills and cliffs. The gondola of the balloon will slowly rotate so that the imagers can get a panoramic view of the surface and atmosphere (i.e., MIDAS can look within a ±30° conical FOR). Tracking of the balloon will also provide local wind velocity data. The distributed aperture system minimizes risk, since single mirror failure cannot result in total imaging system failure, and this system can be then reconfigured with only minor reduction in capability.

4.2 Lidar Imaging

We plan to establish the interfaces between Goddard developed Lidar systems and Lockheed's MIDAS development effort. This is another technology that can be considered already established.

Lidar measurements during the recon phases are required for surface topography and atmospheric winds down to the surface, so that the balloon can navigate safely around Titan. Here, we note that the Huygens probe cameras clearly showed rolling hills with 100 meter heights present at probe's landing site [1], while the Cassini orbiter is only expected to provide ~ 20-30% radar coverage (i.e., topography) of Titan's surface. The Cassini imagers only provide albedo variations on the surface (i.e., no topography information). Lidar altimetry and atmospheric profiling will be done on the orbiter to get the big picture of Titan's surface, atmosphere and haze. The balloon, which will use microwave communications with the orbiter for GPS, is best suited for high resolution Lidar altimetry (topography), Doppler (winds), atmospheric haze and surface composition due to it is close proximity to the surface ($z < 10$ km). This balloon application is similar to Lidar techniques used with airplanes at Earth. In the case of composition measurements, broad-band passive spectroscopic techniques maybe more suited, since lasers can only cover specific molecular lines of interest. The Lidar measurements will look for sites of interest on surface. Active imagery will not be as sensitive to Titan's haze as it is for passive imagery, but we will explore usage of Titan's Near-IR windows that have been used by Cassini cameras and Earth telescopes. Cassini/Huygens measurements of the haze will be used. Techniques have been developed at GSFC to measure winds at Earth from airplanes by bouncing photons off aerosol particles and using Etalon filters [20].

4.3 Sensor Miniaturization

Goddard provided the GCMS for the Huygens Probe [21]. Goddard is developing miniature versions of the IMS as shown in Figure 6. This concept uses carbon nanotubes to provide field emission of electrons for its electron impact ionization source which requires very little power when compared with thermionic emission techniques. It also uses time-of-flight (TOF) technique for the mass determination and miniature ASIC TOF chip which digitizes the measured TOF. ARC is developing miniaturized GC columns [22]. By combining these two technologies one has a GCMS with similar capabilities as that flown on Huygens but with much less mass, power and volume. Other sensor reduction strategies will be explored.

5.0 CONCLUSION

We have described a mission concept for a new mission to Titan with astrobiology being the primary science objective. The mission would involve an orbiter and Aerorover (hot air balloon) with aerobraking being used to put payload in orbit around Titan. The Aerorover will provide 4π *in situ* coverage of the atmosphere and surface of Titan.. The surface is expected to be the most important when it comes to prebiotic chemistry. It is also the

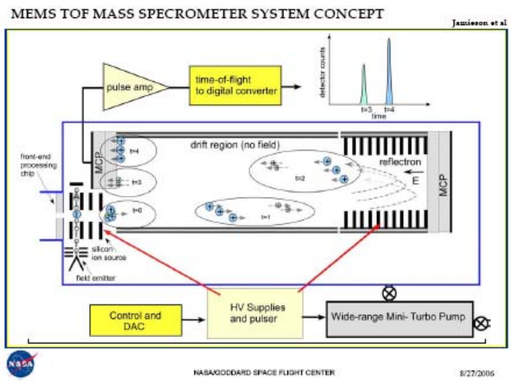

Figure 6. MEMS Ion Mass Spectrometer being developed at GSFC. It uses carbon nanotubes for field emission of electrons to ionize neutral gas entering instrument.

least known. We described most of the technology hurdles to be overcome and plan to reduce risk and cost by partnering with industry, using miniaturization strategies and new technology concepts such as nanotechnology. The recent Cassini/Huygens results have underscored the importance of a new mission to Titan and should be actively considered by the planetary community for the upcoming New Frontiers 2008 opportunity or later strategic flagship opportunities.

6.0 REFERENCES

1. Tomasko, M. G., et al., Rain, winds and haze during the Huygens probe's descent to Titan's surface, *Nature*, **438**, 765-778, 2005.
2. Waite, J. H., et al., Ion Neutral Mass Spectrometer results from the first flyby of Titan, *Science*, **308**, pp. 982-986, 2005.
3. Crary, F. J., et al., Dynamics and composition of plasma at Titan, *Science*, in review, 2006.
4 Niemann, H. B., et al., The abundances of constituents of Titan's atmosphere from the GCMS instrument on the Huygens probe, *Nature*, **438**, 779-784, 2005.
5. Schulze-Makuch, D. and D. H. Grinspoon, Biologically enhanced energy and carbon cycling on Titan?, *Astrobiology*, **5**, 560-567, 2005.
6. Sotin, C., et al., Release of volatiles from a possible cryovolcano from near-infrared imaging of Titan, *Nature*, **435**, 786, 2005.
7. Porco, C. C., et al., Imaging of Titan from Cassini spacecraft, *Nature*, **434**, 159-168, 2005.
8. Elachi, C., et al., Titan Radar Mapper observations from Cassini's T_3 fly-by, *Nature*, **441**, 709-713, 2006.
9. Takano, T., et al., Methane drizzle on Titan, *Nature*, **442**, 432-435, 2006.
10. Sittler, E. C., Jr., et al., Titan Orbiter Aerorover Mission (TOAM), proposal submitted in response to NRA 03-OSS-01-VM, Call for Mission Concepts: Space Science Vision Missions, 2003.
11. Rappaport, N., et al., Doppler measurements of the quadrupole moments of Titan, *Icarus*, **126**, 313-323, 1996.
12. Smith, D. E., et al., Mars orbiter laser altimeter: Experiment summary after the first year of global mapping of Mars, *J. Geophys. Res.*, **106(E10)**, 23689-23722, 2001.
13. Tyler, G. L., et al., Radio science observations with Mars Global Surveyor, *J. Geophys. Res.*, **106(E10)**, 23327-23348, 2001.
14. Lebreton, J.-P. and D. L. Matson, The Huygens Probe: Science, Payload and Mission, *Space Sci. Rev.*, **104**, 59-100, 2002.
15. Zarnecki, J. C., et al., Huygens' surface science package, *Space Sci. Rev.*, **104**, 593-611, 2002.
16. Acuna, M. H., et al., Global distributions of crustal magnetization discovered by the Mars Global Surveyor MAG/ER Experiment, *Science*, **284**, 790-793, 1999.
17. Carlisle, C. C., G. Le, J. A. Slavin, J. T. VanSant, E. H. Webb, Space Technology 5 – Technology Validation Update, *IEEEAC*, paper #1521, 2005.
18. Pitman, J. T., et al, Multiple Instrument Distributed Aperture Sensor (MIDAS) for planetary remote sensing, *Proceedings of SPIE – Volume 5660 Instruments, Science and Methods for Geospace and Planetary Remote Sensing*, C. A. Nardell, P. G. Lucey, J. Yee, J. B. Garvin editors December 2004, 168-180, 2004.
19. Kendrick, R. L., et al., Wide-field Fizeau imaging telescope: experimental results, *Applied Optics*, Vol 45, 4235-4240, 2006.
20. Gentry, B. M. and H. Chen, The Goddard Lidar Observatory for Winds (GLOW), 23rd ILRC in Nara Japan, 24-28 July, 2006.
21. Niemann et al., The Gas Chromatograph Mass Spectrometer Aboard Huygens, *Huygens Science Payload and Mission, ESA Publication SP-1177,* 85, 1997.
22. Kojiro, D., MiniGC-IMS, *15th International Conference on Ion Mobility Spectrometry, July 23-28, 2006, Honolulu, HA,* 2006.